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14. ABSTRACT
This project focused on the fabrication, study and understanding of electronic devices that incorporate nanometer scale magnetic elements. Developments in this area have great potential for ultra-fast, high density, compact, non-volatile and radiation hard magnetic memory, which eliminates moving parts from computers and other portable electronic devices while greatly reducing power consumption. The specific aim of this project period was to investigate the effect of spin-polarized currents on magnetization dynamics in device structures with sub 100mm lateral dimensions and systematically varied composition.

15. SUBJECT TERMS
ferromagnetism; magnetic hysteresis; magnetization reversal; electrical spin injection; spin-transfer; spin dynamics; spintronics; magnetoelectronics; magnetic switching; micromagnetics; magnetic multilayers; nanostructured materials;

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Final Report: N00014-02-1-0995

Contract Information

Contract Number	N00014-02-1-0995
Title of Research	Gate-Controlled Ferromagnetism in Semiconductor Nanostructures
Principal Investigator	Andrew D. Kent
Organization	New York University

Technical Section

Technical Objectives

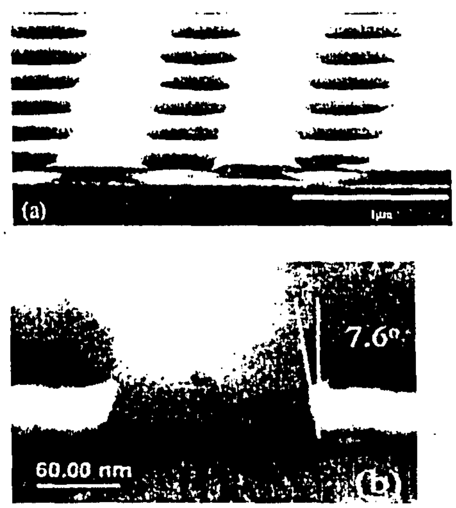
This project focused on the fabrication, study and understanding of electronic devices that incorporate nanometer scale magnetic elements. Developments in this area have great potential for ultra-fast, high density, compact, non-volatile and radiation hard magnetic memory, which eliminates moving parts from computers and other portable electronic devices while greatly reducing power consumption. The specific aim of this project period was to investigate the effect of spin-polarized currents on magnetization dynamics in device structures with sub-100 nm lateral dimensions and systematically varied composition.

Technical Approach

Our technical approach includes: 1) device nanofabrication; 2) high sensitivity magnetotransport and magnetic measurements; 3) high speed electronic measurements to study magnetization dynamics and switching; and 4) micromagnetic modeling of device characteristics

Progress

Nanofabrication: We have developed a technique to fabricate and electrically contact sub-100 nm lateral dimension magnetic thin film elements and multilayers, which does not require ion-milling of the layers (that can induce damage) or extensive (and expensive) processing. The technique employs electron-beam lithography to define an aperture in a thin metal stencil mask (see figure below). A magnetic layer is then grown by electron beam evaporation through the aperture and onto the surface below the stencil. Samples with lateral sizes as small as 30 nm × 60 nm have been fabricated and studied. This technique can be used to integrate metallic magnetic electrodes with semiconductor nanostructures. We have also developed capabilities to systematically vary material composition across wafers using a computer controlled stencil mask in ultra-high vacuum. This latter capability enables efficient studies of the effects of material and layer thicknesses on device characteristics. This nanofabrication technique is presented in an article we published in the Journal of Applied Physics 93, 6859 (2003).



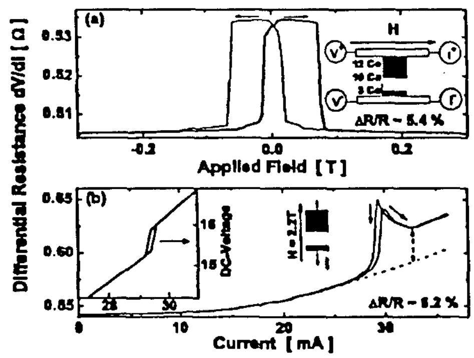


Figure Left: a) Scanning electron microscopy (SEM) image of an array of submicron apertures in a thin metal stencil mask. This new nanostencil process enables fabrication of high density arrays of electrically contacted nanomagnets. b) Transmission electron microscopy (TEM) image of a magnetic nanopillar grown by electron beam evaporation in a nanostencil. The graphic illustrates that the pillar has close to vertical sidewalls. Right: Magnetotransport studies of Co/Cu/Co nanopillars. (a) A magnetic field can switch the device from a high resistance state (with antiparallel alignment of magnetization of the layers) to a low resistance state (of parallel alignment). (b) A spin-current can also switch the device to a high resistance state even in large applied fields. The graphic shows that in a field of 2.2 T a current of 30 mA leads magnetization reversal. This illustrates the efficiency of spin-currents for control of magnetization dynamics

Spin procession and reversal of the magnetization driven by a spin-polarized current: In small magnetic bilayer devices we have found that a spin-polarized current can induce large angle precession and reversal of the magnetization of a magnetic element even in large applied magnetic fields. A paper on these experiments was published in Physical Review Letters **91**, 067203 (2003).

Current-induced excitations in Single Magnetic Layer Devices: Current-induced excitations have been observed for the first time in magnetic nanostructures that only have a single thin magnetic layer. It was generally believed that two magnetic layers were necessary to create excitations, one to polarize the current and the second to respond to the spin-polarized current. A paper on these experiments was published in Physical Review Letters **93**, 176604 (2004).

Current-induced switching in Single Magnetic Layer Devices: Bistable resistance states and switching have been observed in structures with only a single nanomagnetic layer (sub-100 nm,). This result shows that a single magnetic layer can act as a memory element. The switching is between different domain configurations of the layer. These results were reported in Applied Physics Letters **88**, 162506 (2006).

Bipolar high field spin-current driven magnetic excitations: A series of experiments on Co/Cu/Co bilyaers showed that non-uniform spin-wave instabilities compete with uniform magnetic excitations. A paper on this was published in Physical Review B. RC **71**, 140403 (2005). A more recent study shows how these non-uniform spin-wave excitations can be suppressed by properly engineering the contact layers; Journal of Applied Physics 99, 08G511 (2006). This is important for device applications as uniform magnetic excitations are desirable.

Spin-transfer induced precessional magnetization reversal: We discovered a method to induce magnetization reversal of nanomagnets in sub-100 ps time scales using spin-polarized currents. A US

Patent has been granted for this invention: "High Speed Low Power Magnetic Devices Based on Current Induced Spin-Momentum Transfer," inventors: A. D. Kent, E. G. Garcia and B. Oezyilmaz, Assignee: NYU, U.S. Patent No. 6,980,469. (see also, the attached patent report). A paper was also published: Applied Physics Letters **84**, 3897 (2004)

High speed measurements and ferromagnetic resonance studies: We have setup a high speed electrical measurement system to characterize the short time scale response of magnetic devices that employs a 50 GHz sampling oscilloscope. New equipment was also ordered to enable fast pulse generation and noise measurements up to 50 GHz. This setup was used to conduct studies of the magnetization damping and magnetic characteristics of ultra-thin magnetic layers. Initial results are published in Journal of Applied Physics **99**, 08N503 (2006) and a second paper has been submitted to Physical Review B (preprint at: cond-mat/0602243)

Improvements in our UHV system: We have upgraded our UHV thin film deposition system so that we can deposit materials through fine scale metal shadow masks, which we can change in-situ (under computer control) without breaking vacuum. This can be used to deposit electrical gates and test various material combinations and surface preparations in integrating metallic and semiconducting materials.

Publications:

1. J. Z. Sun, D. J. Monsma, T. S. Kuan, M. J. Rooks, D. W. Abraham, B. Oezyilmaz, A. D. Kent and R. H. Koch, "Spin-torque transfer in batch fabricated spin-valve magnetic nanojunctions," Journal of Applied Physics **93**, 6859 (2003)
2. B. Oezyilmaz, A. D. Kent, D. Monsma, J. Z. Sun, M. J. Rooks and R. H. Koch, "Current-induced magnetization reversal in high magnetic fields in Co/Cu/Cu Nanopillars," Physical Review Letters **91**, 067203 (2003)
3. A. D. Kent, B. Özyilmaz and E. del Barco, "Spin-Transfer Induced Precessional Magnetization Reversal," Applied Physics Letters **84**, 3897 (2004)
4. B. Özyilmaz, A. D. Kent, J. Z. Sun and R. H. Koch, "Current Induced Excitations in Single Cobalt Ferromagnetic Layer Nanopillars," Physical Review Letters **93**, 176604 (2004)
5. M. Zimmler, B. Oezyilmaz, W. Chen, A. D. Kent, J. Z. Sun, M. Rooks and R. Koch, "Current-induced effective magnetic fields in Cu/Co/Cu Nanopillars," Physical Review B **70**, 184438 (2004)
6. B. Özyilmaz, A. D. Kent, M. J. Rooks and J. Z. Sun, "Bipolar high field excitations in Co/Cu/Co Nanopillars," Physical Review B, Rapid Communications **71**, 140403 (2005)
7. J. Z. Sun, B. Ozyilmaz, W. Chen, M. Tsoi, A. D. Kent, "Spin-transfer-induced magnetic excitations: the role of spin-pumping induced damping," Journal of Applied Physics **97**, 10C714 (2005)
8. J-M. L. Beaujour, W. Chen, A. D. Kent and J. Z. Sun, "Ferromagnetic resonance study of polycrystalline Cobalt ultrathin films," Journal of Applied Physics **99**, 08N503 (2006)
9. W. Chen, A. D. Kent, M. J. Rooks, N. Ruiz, J. Z. Sun, "Spin-transfer-induced excitations in bilayer magnetic nanopillars at high fields: The effects of contact layers," Journal of Applied Physics **99**, 08G511 (2006)
10. B. Özyilmaz and A. D. Kent, "Current-induced switching in single ferromagnetic layer nanopillar junctions," Applied Physics Letters **88**, 162506 (2006).
11. J.-M. L. Beaujour, J. H. Lee, A. D. Kent, "Magnetization damping in polycrystalline Co ultra-thin films: Evidence for non-local effects," submitted to Physical Review B (preprint at: cond-mat/0602243)

Patents

"High Speed Low Power Magnetic Devices Based on Current Induced Spin-Momentum Transfer," inventors: A. D. Kent, E. G. Garcia (E. del Barco) and B. Oezyilmaz, Assignee: NYU, U.S. Patent No. 6,980,469.

Spin Transport in Ferromagnetic Nanostructures
New York University
URL: http://www.physics.nyu.edu/kentlab/

Objectives

- To fabricate and study electronic devices that incorporate nanoscale magnetic elements;
- To develop methods for creating local spin-polarization and spin-polarized currents in nanostructures;
- To employ spin-polarized currents to control magnetic dynamics on the nanoscale.

DOD Relevance

New nanoscale electronic devices that integrate semiconductor information processing with non-volatile magnetic memory.

Approach

- Development and use of new nanofabrication techniques for ferromagnetic and semiconductor nanostructures;
- UHV thin film deposition through metal stencil masks for rapid material/device prototyping;
- Magnetotransport and magnetic measurements of nanostructures;
- High speed electronic measurements to study magnetization dynamics and switching;
- Micromagnetic modeling.

Spin Transport in Ferromagnetic Nanostructures
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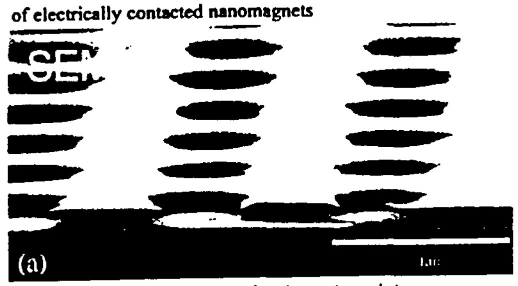
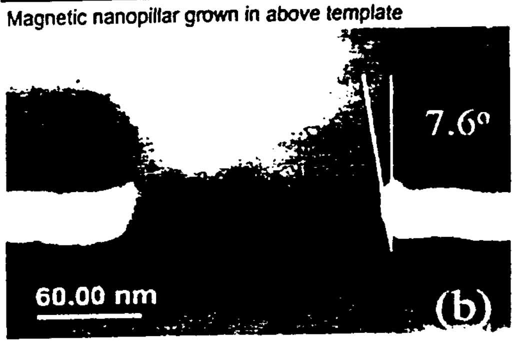
URL: http://www.physics.nyu.edu/kentlab/

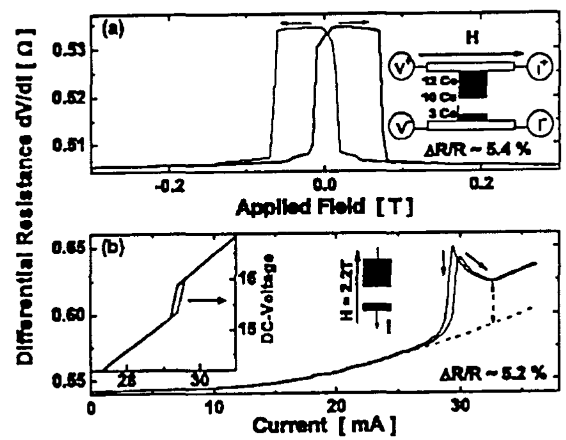
Research Highlights

A new nanostencil process enables fabrication of high density arrays of electrically contacted nanomagnets



Magnetic nanopillar grown in above template





Magnetotransport studies of Co/Cu/Co nanopillars show that a spin-current can induce magnetization reversal even in large applied fields. This illustrates the efficiency of spin-currents for control of magnetization.

Published in Physical Review Letters 91, 067203 (2003).

- Developed a nanostencil technique to fabricate and contact arrays of sub-100 nm lateral dimension magnetic thin film elements on semiconductor substrates;
- Developed capabilities to systematically vary material composition across wafers for efficient and rapid materials studies using computer controlled stencil masks in UHV;
- Demonstrated that spin-polarized currents can induce large angle magnetization precession and reversal in magnetic elements even in large applied fields.

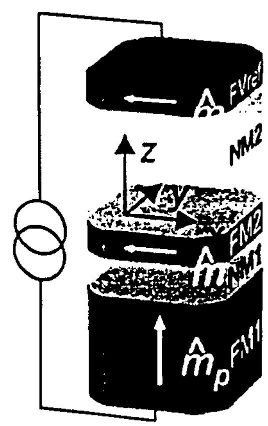
Spin Transport in Ferromagnetic Nanostructures

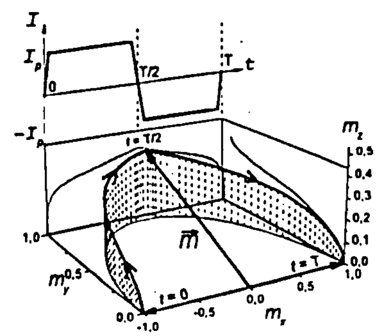
New York University

URL: http://www.physics.nyu.edu/kentlab/

Research Highlights

A magnetoelectronic device has been invented in which a spin-current pulse produces a rapid and coherent magnetization reversal of a thin film nanomagnet.



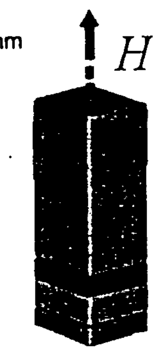


The reversal time can be less than 50 ps! Device is low-power, fast, non-volatile and can be realized with present day nanomagnet technology.

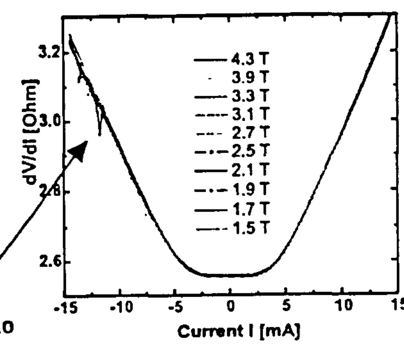
A. D. Kent et al., Applied Physics Letter **84**, 3897 (2004) and "High Speed Low Power Magnetic Devices Based on Current Induced Spin-Momentum Transfer," Patent Application Publication, US 005/0041462 A1, Feb. 24, 2005.

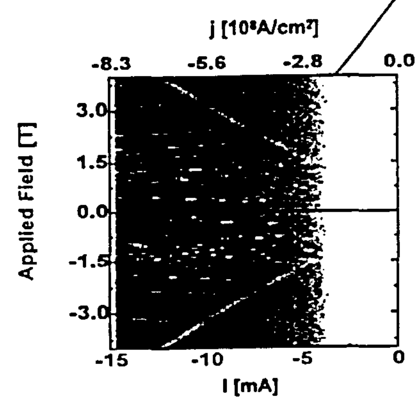
Research Highlights

Current induced excitations have been observed for the first time in nanostructures that only have *a single* thin magnetic layer.



Excitations observed for only one polarity of the current in asymmetric structures.





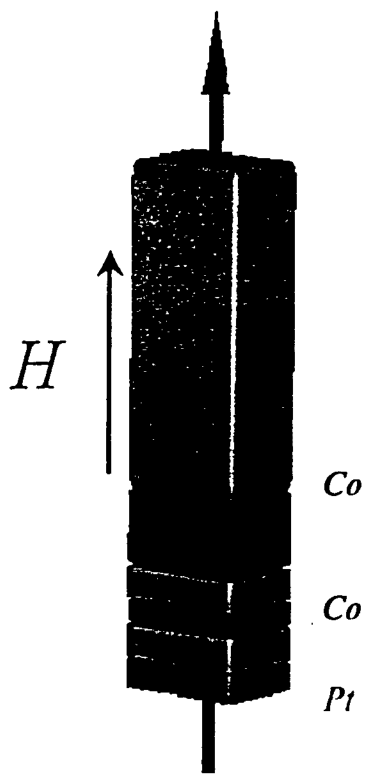
Device dV/dI on gray scale vs current and applied field.

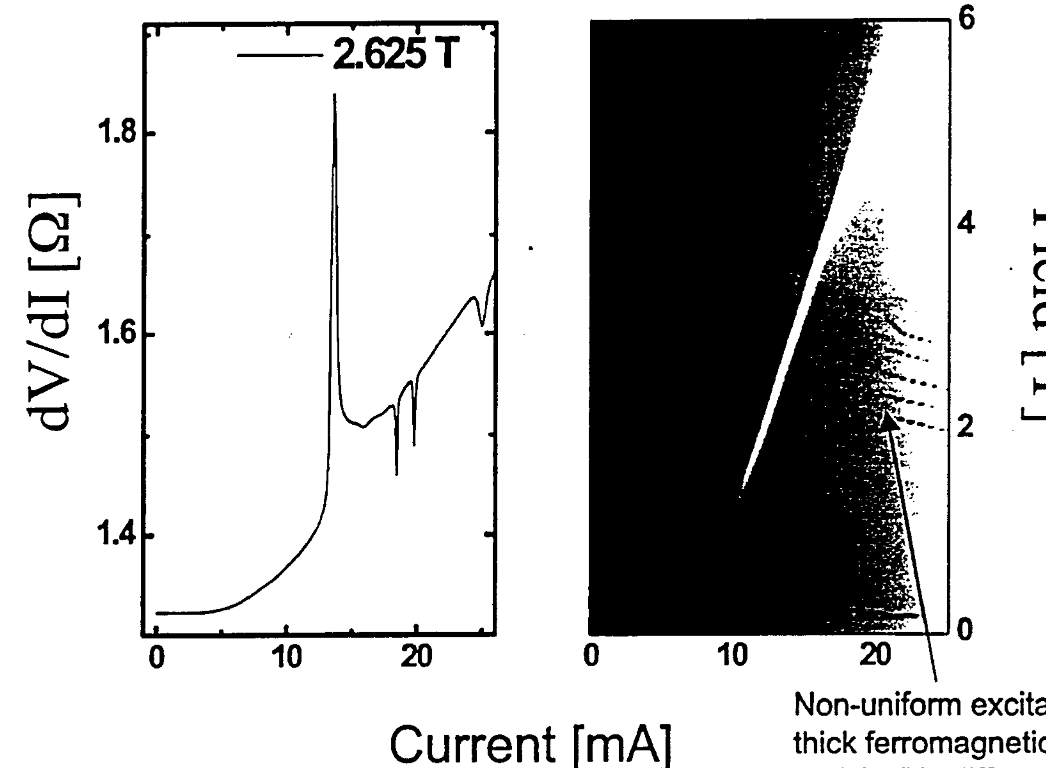
Note excitations lead to a decrease in device resistance!

Published in Physical Review Letters **93**, 176604 (2004)

Research Highlights

Bipolar high field spin-current driven magnetic excitations have been observed in Co/Cu/Co nanopillars. These results show that non-uniform spin-wave instabilities compete with uniform magnetic excitations.





Non-uniform excitation of the thick ferromagnetic layer appear as "dips" in differential resistance.

Published in Physical Review B RC 71, 140403 (2005)